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# A ribbon of dark water: phytoplankton blooms in the meanders of the Pacific North Equatorial Countercurrent

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**Abstract**

In the far southwestern corner of the North Pacific Ocean, the Mindanao Current retroflects and flows northeast into the nascent North Equatorial Countercurrent (NECC). Ocean-color images show that phytoplankton blooms occur both in the nearly closed cyclonic loop of the retroflection, and in the meandering NECC, which were particularly strong during the El Niño event of 1997–98. In the winter of 1997–98, the bloom persisted for about 4 months, and, at its peak, extended for several thousand kilometers along the current stream. The NECC meanders are observed in SeaWiFS and OCTS images at various times throughout the nearly 5 years of data examined, but regionally averaged chlorophyll concentrations during the 1997–98 El Niño were higher than at any time since. The current meanders are sometimes visible in SeaWiFS images during winter, spring and summer, but not in autumn, consistent with the seasonal cycle of formation and decay of the Mindanao Dome (MD). Although the MD has a cyclonic circulation pattern, vertical nutrient flux appears to be maximal in the NECC, which forms its southern boundary, rather than in the MD itself. The appearance of phytoplankton blooms along the stream of the NECC is most plausibly attributed to upwelling associated with current meandering, although El Niño-induced shoaling of the thermocline and seasonal Ekman pumping also may contribute. In addition, transport of nutrient-rich water from the South Pacific by the New Guinea Coastal Undercurrent (NGCUC), which is maximal in boreal winter, creates a gradient of nutrient concentration across the NECC stream with much greater concentrations to the south at a given density (J. Geophys. Res. 103 (1998) 12959). In 1997-98 a confluence of all of these factors occurred. Shoaling of the thermocline and an intensified NECC due to the El Niño event coincided with the seasonal formation of the MD and increased westward transport of nutrient-rich water by the NGCUC to produce the highest chlorophyll concentrations observed in 5 years of ocean-color data. Similar though weaker blooms were observed in the spring of 2003 in association with the very weak 2002–03 El Niño.


## 1. Introduction

Satellite observations of ocean color provide a tool for oceanographers to identify flow patterns and hydrographic boundaries on a large scale but

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at very high resolution (up to 1 km). Ocean-color images can reveal subsurface processes (entrainment of nutrients into the mixed layer) and dynamic features not visible in sea-surface temperature (e.g., Murtugudde et al., 1999). Similarly, waters with very different physical properties and flow characteristics may be indistinguishable in ocean-color images.

Near its source region, the Pacific North Equatorial Countercurrent (NECC), meanders much like western boundary currents such as the Gulf Stream and the Kuroshio, but on a much smaller scale (Lukas et al., 1991). Upwelling associated with current meandering and the resulting enhancement of biological production have been observed in the Gulf Stream (Osgood et al., 1987; Bower and Rossby, 1989; Hitchcock et al., 1993; Ashjian et al., 1994; Mariano et al., 1996). The underlying mechanisms are not completely understood, but to first order can be understood as arising from conservation of potential vorticity (PV). If the surface layer has a thickness $D$, the PV of this layer is $(f + \zeta)/D$ where $f$ is the planetary vorticity and $\zeta$ the relative vorticity (Pond and Pickard, 1983). The increase in $f$ that occurs when the meandering current flows poleward can be compensated either by cyclonic curvature of the flow (decreasing $\zeta$) or vertical motion (increasing $D$) so that $PV$ is conserved (Hitchcock et al., 1993). Divergence (upwelling) occurs downstream of cyclonic meanders (troughs) and convergence (downwelling) occurs downstream of anticyclonic meanders (crests) (Bower and Rossby, 1989; Bower, 1989; Flierl and Davis, 1993; Yoshimori, 1994). In this paper we analyze ocean colour images of the nascent NECC, and use ancillary data and an ocean general circulation model (OGCM) to argue that meander-induced upwelling appears to be a proximate control on the supply of nutrients to the surface, but that the flux is also controlled by subsurface environmental conditions (thermocline depth, water mass structure) that change more gradually and are coherent with basin-scale climate fluctuations.

The currents in this region were extensively studied during the Western Equatorial Pacific Ocean Circulation Study (WEPOCS) (Lindstrom et al., 1987; Lukas et al., 1991; see Fig. 1). The NECC was observed to have a subsurface core at about 120 m in meridional transects at 143°E (Lindstrom et al., 1987). Lukas et al. (1991) concluded that Mindanao Current (MC) water contributes to the NECC via cyclonic retroflection in the Celebes Sea. The general features of the regional hydrography and circulation are illustrated in Fig. 1. (We caution that not all place names and circulation features referred to in the text are indicated on this map, and one feature is given a different name than that used by Fine et al. (1994), as discussed below). The MC flows southward along the east coast of Mindanao, retroflects as it approaches the equator, and turns to the northeast to contribute to the nascent NECC, whose meanders are indicated in Fig. 1. To the north of this current is a small cyclonic gyre called here the Mindanao Eddy, which we will refer to as the Mindanao Dome (MD) following Masumoto and Yamagata (1991). In the seasons when the MD is present (roughly the first half of the calendar year), its zonal extent is much larger than is implied in Fig. 1, extending eastward of 140°E (Masumoto and Yamagata, 1991). The New Guinea Coastal Undercurrent (NGCUC) flows northwest along the north coast of New Guinea and feeds the eastward flowing equatorial undercurrent (EUC). We will argue below that the NGCUC may be an important source of nutrients for phytoplankton in the NECC.

The biogeochemistry in this region is complicated because of the confluence of many water masses (Tsuchiya et al., 1989; Fine et al., 1994). Data from WOCE section P9 show a large range of variation of nitrate and silicate concentrations, at similar densities, between the equator and 10°N (Kaneko et al., 1998). East of 140°E the NECC follows a strong salinity and potential vorticity front (Gouriou and Toole, 1993), and nitrate concentration appears to increase markedly from north to south across this front (Kaneko et al., 1998). The NGCUC transports both nutrient-rich South Pacific Tropical Water (SPTW) and nutrient-poor Antarctic Intermediate Water (AAIW) (Tsuchiya et al., 1989; Fine et al., 1994; Kashino et al., 1996; Kuroda, 2000). The latter occurs at densities exceeding 1026.8 kg m$^{-3}$ and is not entrained into the surface currents (Fine et al., 1994). The former occurs at shallower depths, and we hypothesize that it is a significant source of nutrients to the phytoplankton blooms in the NECC. This hypothesis is discussed at length below. The NGCUC also may be enriched in iron from geothermal activity or fluvial sediment (Obata et al., 1993; Mackey et al., 2002), but it is not known whether iron or major nutrients limit productivity in this region.